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Ice Damage in a Chronosequence of Agroforestry Pine Plantations in Arkansas, USA

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Ice Damage in a Chronosequence of Agroforestry Pine Plantations in Arkansas, USA

David M. Burner
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ABSTRACT. Acute (broken and leaning) and transient (bending) damage to loblolly pine (*Pinus taeda* L.) were assessed in a case study of experimental agroforestry plantations following a December 2000 ice storm. Stand ages were 7-, 9-, and 17-years-old and tree density ranged from 150 to 3,360 trees ha^{-1} in rectangular and multi-row configurations. Wider tree spacing or lower stand density of 7-year-old trees increased stem breakage, while closer spacing increased bending. There was substantial straightening of bent 7-year-old trees 8 months after the storm, and this recovery was determined more by degree of initial bend rather than height or diameter. Nine-year-old loblolly pine had 19% more top breakage and 59% more stem breakage than shortleaf pine (*P. echinata* Mill.) ($P < 0.001$). Agroforestry design influenced ice damage in 7-year-old stands, but no design had catastrophic loss. Thinning from above caused an increased susceptibility of ice damage to a 17-year-old stand compared to a nonthinned stand. The case study supports the cultivation of loblolly pine in areas prone to ice damage. *[Article copies available for a fee from The Haworth Document Delivery Service: 1-800-HAWORTH. E-mail address: <docdelivery@haworthpress.com> Website: <http://www.HaworthPress.com>]*

KEYWORDS. Climatic effects, glaze damage, *Pinus echinata*, *Pinus taeda*, plantation, row thinning, stand density, stand management

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INTRODUCTION

Freezing precipitation occurs throughout most of the USA and Canada, frequently in central and eastern USA north of 32°N. Freezing rain has significant potential for rapid ice accumulation (Cortinas et al., 2000). Ice deposition can place tremendous weight loads on the tree, increasing twig weight as much as 30 times (Oliver and Larson, 1996), depending on storm duration (Robbins and Cortinas, 1996). Potentially damaging ice storms may be expected within the natural range of loblolly pine (*Pinus taeda* L.) once every 6 years (Schultz, 1997). Tree species and topography also influence the local impact of a particular ice storm (Warrillow and Mou, 1999; Mou and Warrillow, 2000). The complex interaction of these genetic and environmental factors make it difficult to objectively compare damage assessments and management strategies from different storm events. Thus, ice damage assessments should be considered as case studies. Two ice storms of historical magnitude occurred in Arkansas in mid- and late-December 2000 (Presley, 2001). The first storm mainly affected south central Arkansas (Presley, 2001). The second storm affected southwest and west central Arkansas with 5 to 7 cm ice accumulation in some areas (Anderson, 2000). Timber damage from the latter storm was severe, with early estimates of 27,500 ha of private, nonindustrial timber completely lost, and 54,700 ha damaged (Plunkett, 2000; Associated Press, 2001).

Standard silvicultural practices can help minimize ice damage to loblolly stands (Shepard, 1978; Zeide and Sharer, 2000). Maintaining large, symmetric crowns and root systems (through wide spacing, thinning from below, and judicious pruning) may mitigate the damaging effects of ice loading on loblolly pine (Fountain and Burnett, 1979; Schultz, 1997; Zeide and Sharer, 2000). Forked and diseased trees also may be more susceptible to ice damage (Amateis and Burkhart, 1996; Belanger et al., 1996). Agroforestry stands could be more susceptible to ice damage than natural stands if the planting design or management does not foster crown symmetry.

Acute ice damage, such as breakage of branches and stems, and uprooting, can be readily assessed, unlike long-term damage. Loblolly pine trees with three or more live limbs should survive following storm damage (Barry et al., 1998), indicating that stem damage must be severe to cause mortality. While post-storm mortality may be relatively low following stem breakage (Belanger et al., 1996), future merchantability can be affected due to loss of wood volume, wood damage from pathogens and pests, or poor form. Belanger et al. (1996) found that loblolly pine trees that had suffered ice breakage had 37% less radial and basal area growth than undamaged trees during a 5-year post-storm period.

There have been few reports documenting the recovery of ice damaged loblolly pine, particularly the recovery from stem bending. The literature also is contradictory whether ice damage of loblolly pine is affected by tree spacing (Burton, 1981; Amateis and Burkhart, 1996) or thinning (Burton, 1981; Belanger et al., 1996). Accurate damage assessment and understanding of tree recovery are needed to assure sound post-storm management decisions.

The late-December 2000 ice storm provided a rare opportunity to examine damage to agroforestry stands. We quantified ice damage in a chronosequence of agroforestry pine plantations (7-, 9-, and 11-years of age), capturing the changing effect of ice damage on young stands and the ability of the 7-year-old stand to recover from the event.

MATERIALS AND METHODS

Experimental Areas

The experiment was conducted at about 35°N lat., 94°W long., 45 m a.s.l., near the Dale Bumpers Small Farms Research Center, Booneville, Arkansas. The ice storm began the evening of 24 December and continued through 26 December, followed by about 50 mm of snow on 31 December 2000. About 52 mm of melted precipitation was recorded at Site 2 for the period 24 through 31 December 2000. Damage was attributed solely to ice loading because wind was not associated with this storm. It was likely that storm characteristics (precipitation, air, temperature, and wind speed) did not differ substantially among sites as they were separated by a maximum distance of only 8 km. However, ice damage was assessed differently at each site because tree age, and resultant damage, suggested different sampling protocols.

(Site 1)–The soil was a Leadville silt loam (fine-silty, siliceous, thermic Typic Fragiudults) (Garner et al., 1980). Loblolly pine seedlings were planted in 13, 0.4-ha configurations in each of three replicates in 1994. Alleys between tree rows were used intermittently for hay production and there was no known application of soil amendments prior to or since tree planting. Trees had not been thinned or pruned. Rectangular designs were:1.2 m within-row × 2.4 m among row, 1.2 × 3.6, 1.2 × 4.9, 2.4 × 2.4, 2.4 × 3.6, 2.4 × 4.9, 3.6 × 2.4, 3.6 × 3.6, and 3.6 × 4.9. Multi-row (or aggregate) designs were 2 rows of (1.2 m within-row × 2.4 m among row) + 7.3 m alley, 3 rows of (1.2 × 2.4) + 9.7 m, 4 rows of (1.2 × 2.4) + 12.2 m, and 5 rows of (1.2 × 2.4) + 14.6 m. Tree rows were oriented E-W. Thus, the experiment consisted of nine rectangular configurations (alley widths ≤ 4.9 m) and four multi-row configurations (alley widths ≥ 7.3 m). The experiment was a randomized complete block design with three replicates.

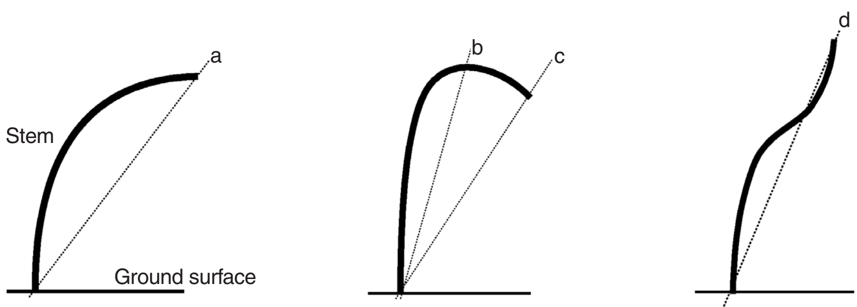
Ice damage was rated in February 2001. One interior tree row within each configuration was selected at random. Two individuals, rating separately, assigned trees to each of six damage classes: stem straight and unbroken (leaning

≤ 15°), tree leaning ≥ 15° from base, top ≤ 25% of stem broken, bottom ≥ 75% of stem broken, stem with a 1st order bend (one inflection point but stem base otherwise straight), and stem with a 2nd order bend (two inflections). Shapes of bent stems are depicted in Figure 1. Because most of the damage in February was due to bending, the same trees were evaluated by the same pair of raters in August 2001 to assess recovery. Trees in August were rated as straight and unbroken, 1st order bend, 2nd order bend, and sigmoid (two inflections). Trees that had been rated in February as having top breakage, stem breakage, or severe lean were deleted from the August evaluation. Sample size ranged from about 3 to 8% of trees per configuration and replication. Height (base to tip) and stem diameter (at 1.4 m above ground surface) (dbh) of 10 straight, unbroken trees were measured in the rated rows in August 2001 to determine whether tree size differed among configurations.

Ten trees in each of the 1st and 2nd order classes were selected in one replicate of the 1.2 m × 2.4 m and 3.6 m × 4.9 m plots. Trees were tagged, and dbh, height (height from ground surface of stem or stem apex), and stem deflection (angles a through d measured from stem base to apex, Figure 1) were measured in February and September 2001.

(Site 2)–The soil was a Linker fine, sandy loam (fine-loamy, siliceous, thermic Typic Hapludults) (Garner et al., 1980). Loblolly and shortleaf (*P. echinata* Mill.) pines were planted separately in spring 1992 in 4-row plots in a rectangular design (1.2 m within rows, 30.4 m long × 4.9 m alley). Trees were planted in N-S orientation with a 24.5 m alley separating each replicate. The experiment was a randomized complete block design with six 0.12-ha replicates. Shortleaf and loblolly pine had been pruned to 8.5 and 9.0 cm diameter outside bark, respectively, in August 1999, but had not been thinned. Tall fescue (*Festuca arundinacea* Schreb.) and orchardgrass (*Dactylis glomerata* L.)

FIGURE 1. Graphic representation of loblolly pine stems (heavy lines) bent from the ice storm: 1st order (left), 2nd order (middle), and sigmoid (right) shapes. Angle of stem deflection was measured as indicated by dashed lines.



had been grown in the alleys with about 200 kg N, P, and K ha^{-1} applied in 2000. Tree height and diameter were measured in August 2000. All trees were examined for ice damage in January 2001 by one rater from site 1 and assigned to the following classes: unbroken, top $\leq$ 25% of stem broken (top), broken stem ($\leq$ five branches remaining), and severe ($\geq$ 15°) lean. An overall damage score was calculated from the ratio of broken tops, stems, and leaning stems to total trees. The experiment was a randomized complete block design with six replicates.

(Site 3)–The soil was a Leadville silt loam (as in Site 1). Loblolly pine was planted in 1984 in N-S rows with an initial spacing of about 1.5 m within rows $\times$ 3.0 m among rows, or 2,225 trees ha^{-1}. In 1998, part of the stand was thinned and the other part was left nonthinned. Ice damage was measured in these adjoining areas that differed in tree density.

The high density treatment had been used for pine straw research and contained about 47 m^2 basal area ha^{-1}. It covered 4.3 ha and had about 1,600 surviving trees ha^{-1} which had not been thinned or pruned. Random subplots comprising half of the stand area were fertilized annually from 1994 through 1999 with 50 kg N and 56 kg P ha^{-1}. Fertilization and pine straw raking regime had not significantly affect dbh, basal area, or survival when measured in 2001 (unpublished data). Three tree rows were selected at random for damage rating without regard to the fertilized subplots. Sample size was about 340 trees (5%).

The low density treatment covered 10.5 ha. Trees were commercially thinned from above to a multi-row configuration of 4 rows of (3.6 $\times$ 3.6 m) + 7.3 m alley in 1998, leaving about 150 trees ha^{-1}. Six interior rows were selected at random for damage assessment. Sample size was about 240 trees (15%). Tree height and diameter were not measured.

Ice damage was scored separately by the same two raters from site 1 in February 2001. Damage classes were: stem straight and unbroken, top $\leq$ 10% of stem broken, middle 11 to 50% of stem broken, bottom $\geq$ 50% of stem broken, 2nd order bend, and severe ($\geq$ 15°) lean.

Statistical Analyses

Damage counts were expressed as a percentage of total trees in the row, and percentages were standardized by square root transformation (Steel and Torrie, 1980). Rectangular and multi-row configurations at Site 1 were analyzed separately using a mixed effects model (PROC MIXED, SAS, 1998) in which evaluation date, tree spacing, and date $\times$ spacing were fixed effects; and rater, replication, date $\times$ rater, rater $\times$ spacing, and date $\times$ rater $\times$ spacing were random effects. For rectangular configurations, linear and quadratic regression effects also were examined to determine whether damage was associated with stand density (trees ha^{-1}) (TPH), row spacing, within-row spacing, and area $tree^{-1}$ (within row × row spacing). Regression effects were not tested in multi-row configurations because there were only two stand densities.

For Site 2, damage classes were subjected to analysis of variance (PROC MIXED, SAS, 1998) to determine whether there were differences between the two tree species. The two densities at Site 3 were compared using PROC MIXED (SAS, 1998) in which tree density was the fixed effect, and replication, rater, and interactions were random effects. Standardized means were untransformed for presentation in tables using the equation (transformed mean)^2 + error mean square (Steel and Torrie, 1980).

RESULTS

Site 1 Rectangular Configurations–Initial Damage

Ice damage to the 7-year-old stand was substantial as only about 10% of the trees were straight (Table 1). About 12% of trees had broken stems at 840 TPH. There were fewer trees with broken (range 1.9 to 11.7%) or leaning stems (0.9 to 7.1%) compared to those that were bent (14.0 to 71.5%), suggesting that much of the damage could be transient. Tagged trees with 1st order bend averaged 32° deflection (Figure 1, angle a). Second order bent trees averaged 39° at maximum trunk inflection, increasing to 54° at the tip (Figure 1, angles b and c).

Trees in rectangular configurations averaged 6.2 m tall and 13.0 cm diameter. Stand density was negatively correlated with diameter (R^2 = 0.68, $P < 0.001$), but tree height and density were not significantly correlated ($P > 0.05$). Top (R^2 = 0.25, $P < 0.01$) and stem breakage (R^2 = 0.39, $P < 0.001$) were positively correlated with diameter, and 2nd order bending was negatively correlated with diameter (R^2 = 0.17, $P < 0.05$). Height was not significantly associated with ice damage ($P > 0.05$).

Analysis of variance indicated significant differences in damage among the rectangular configurations. Damage was associated with stand density, row spacing, within-row spacing, and area $tree^{-1}$. The percentage of trees with 2nd bend in February increased linearly with stand density but the association was weak (R^2 = 0.14, $P < 0.05$). The percentage of leaning trees also was associated with stand density, decreasing and then increasing quadratically (R^2 = 0.37, $P < 0.001$). In February, the percentage of straight trees increased quadratically with row spacing (R^2 = 0.38, $P < 0.05$), and the percentage of 2nd order bent trees decreased linearly with row spacing (R^2 = 0.30, $P < 0.10$). The percentage of top (R^2 = 0.14, $P < 0.05$) and stem (R^2 = 0.33, $P < 0.01$) breakage increased with area $tree^{-1}$.

TABLE 1. Percentage of 7-Year-Old Loblolly Pine Trees in Various Ice Storm Damage Classes in Site 1 Rectangular Alley Configurations, West-Central Arkansas

Rectangular configuration	Stand density (TPH)	Damage class: Straight Feb.	Straight Aug.	Top broken[1]	Stem broken[1]	1st order bend Feb.	1st order bend Aug.	2nd order bend Feb.	2nd order bend Aug.	Lean[1]	Sigmoid-shaped[2]
						(%)					
3.6 m × 4.9 m	560	7.9[3]	57.2	5.3	7.0	42.8	4.3	32.8	0.5[4]	2.5	25.9
3.6 m × 3.6 m	750	10.5	44.6	12.5	8.3	36.7	7.4	28.1	0.5[4]	0.9[4]	25.0
2.4 m × 4.9 m	840	14.2	50.5	7.4	11.7	26.5	3.8	41.6	0.5[4]	6.4	28.5
3.6 m × 2.4 m	1120	2.1	60.2	3.5	2.5	27.9	3.6	64.1	0.5[4]	1.6	29.8
2.4 m × 3.6 m	1120	10.1	52.2	3.3	6.3	28.1	3.4	50.3	2.9	2.8	28.4
2.4 m × 2.4 m	1680	3.7	35.7	4.6	6.4	14.0	12.1	71.5	4.1	0.9[4]	31.1
1.2 m × 4.9 m	1680	19.8	65.1	10.3	5.0	31.4	4.2	33.4	0.5[4]	0.9[4]	17.7
1.2 m × 3.6 m	2240	11.4	63.6	2.9	3.4	30.0	6.2	56.2	1.3	0.9[4]	27.0
1.2 m × 2.4 m	3360	6.2	50.6	2.3	1.9[4]	26.7	13.0	58.9	7.5	7.1	26.5
LSD (0.05)[5]		7.6	5.2	8.7	8.6	6.0	NS	7.9	2.4	4.0	5.6
Density effect[6]		NS	NS	NS	NS	NS	NS	Linear	NS	Quad	NS

[1] Broken and leaning trees were disregarded from the August evaluation. [2] The sigmoid category was rated in August only. [3] Analysis was based on square root-transformed data but untransformed means are shown. [4] Transformed mean = 0. [5] Least significant difference for comparing means within columns. [6] The regression effect of stand density (trees ha^{-1}) was either non- significant (NS) at $P \leq 0.10$, linear ($P < 0.05$), or quadratic ($P \leq 0.001$) (Quad).

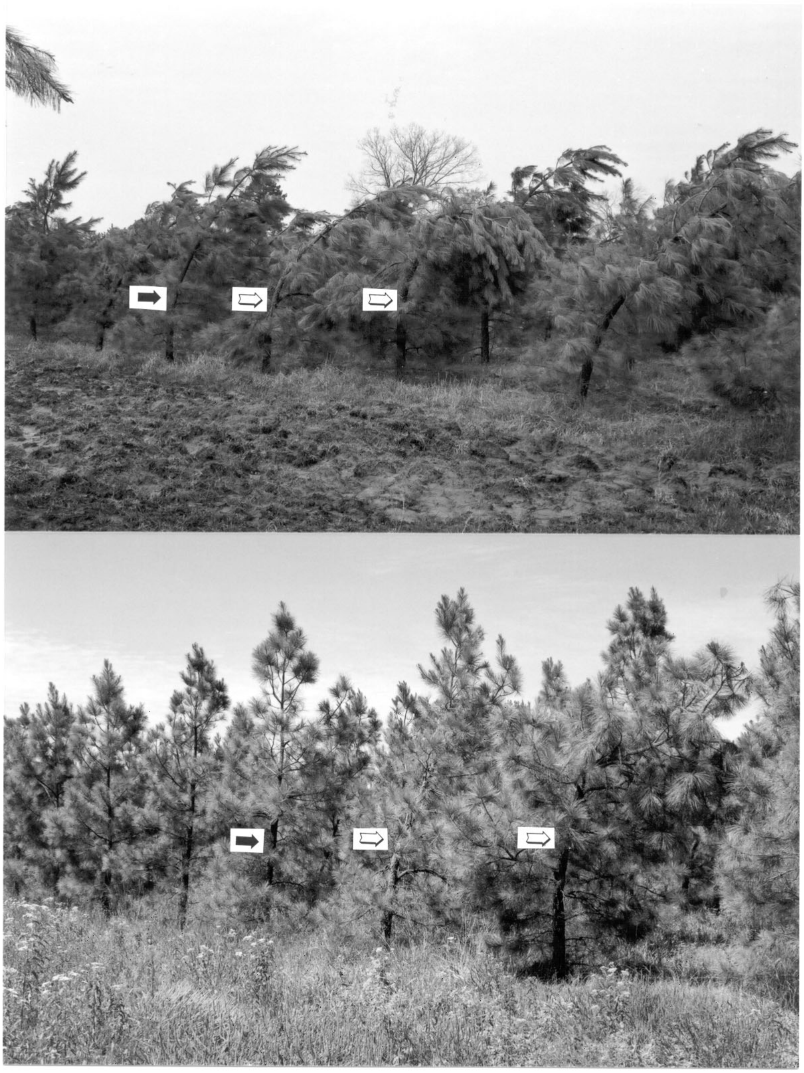
While ice damage clearly differed with spacing and stand density, effects were not always predictable. Two pairs of configurations had 1120 TPH and two pairs had 1680 TPH, but within these pairs of treatments some damage scores differed ($P < 0.05$). For these pairs of treatments, there were more straight trees and fewer 2nd order bent trees in February for configurations with closer than wider within-row spacing ($P < 0.05$). The findings were consistent with what we found across treatments, where the percentage of straight trees decreased quadratically ($R^2 = 0.26$, $P < 0.01$) while trees with stem breakage increased ($R^2 = 0.29$, $P < 0.01$) as within-row spacing increased. There also was a weak quadratic increase in percentage of 1st order bent trees with increasing within-row spacing ($R^2 = 0.18$, $P < 0.01$). Thus, damage was minimized by close within-row spacing. Tree size did not adequately explain differences in ice damage within these pairs of treatments. Trees at the 1.2 m × 4.9 m spacing were taller (6.0 vs. 5.3 m) and had larger diameter (12.0 and 9.5 cm) than those at the 2.4 × 2.4 m spacing, but there were no significant size differences for trees at 1120 TPH ($P > 0.10$).

Site 1 Rectangular Configurations–Recovery

Means of straight and 1st and 2nd order bent trees differed significantly between dates ($P \leq 0.05$) indicating that there was rapid recovery of bent trees 8 months after the storm (Table 1). From February to August, the percentage of straight trees increased while there was a concomitant decrease in 1st and 2nd order bent trees. It was likely that more 1st order than 2nd order bent trees straightened during this time, as many of the 2nd order bent trees assumed a sigmoid-shape (Figure 2). However, substantial numbers of both 1st and 2nd order bent trees straightened to account for the number of straight trees in August. The percentage of 2nd order bent trees in August decreased quadratically with area tree^{-1} ($R^2 = 0.39$, $P < 0.001$). This might have been associated with a decreased percentage of 2nd order bent trees in wider rows in February (mentioned above) and not that wide spacing facilitated straightening. The 1st and 2nd order tagged trees did not differ in diameter ($P = 0.09$), although spacing ($P < 0.001$) and the date × spacing interaction effects ($P < 0.01$) on diameter were significant. As expected, diameter increased proportionately more between February and September (10.7 and 13.4 cm, respectively) at the wider (3.6 m × 4.9 m) configuration than it did at the narrower (1.2 m × 2.4 m) spacing (8.9 and 10.4 cm).

Bend angle of tagged trees decreased (trees became more erect) between February and August (43 vs. 6°, respectively) ($P < 0.001$). Rate of recovery was influenced by the order of initial bend more than diameter. For 1st order bent trees, nine of 10 were rated as straight in the narrow configuration when

FIGURE 2. Photographs of 7-year-old loblolly pine trees in a 3.6 × 4.9 m configuration in February (top) and August (bottom) taken from about the same perspective. Note that tree with a 1st order bend in February was straight in August (closed arrows), while trees with a 2nd order bend assumed a sigmoid shape (open arrows).



reexamined in September. Similarly, seven of 10 straightened in the wide configuration. Thus, 1st order bent trees tended to straighten. Recovery was not so rapid for 2nd order bent trees. In the narrow configuration, one 2nd order bent tree became straight, two became 1st order, six assumed a sigmoid-shape, and one was unchanged. For 2nd order bent trees in the wide configuration, none was straight in September, while three were 1st order and seven were sigmoid-shaped. Many of these sigmoid-shaped trees should eventually straighten based on their small stem deflections (range 7 to 16°), but their recovery was clearly not as rapid as that of 1st order bent trees.

Site 1 Multi-Row Configurations

Percentages of trees in the various damage classes in multi-row configurations (Table 2) were roughly comparable to those in the rectangular configurations. Three multi-rows had about 1,580 TPH and did not differ for most damage classes. The stand with highest density (1,980 TPH) had fewer straight trees and more 2nd order bending than the lower density configurations ($P \leq 0.05$). Damage was not associated with height (mean = 6.3 m), but 2nd order bending was negatively correlated ($R^2 = 0.49$, $P = 0.01$) with diameter (mean = 11.3 cm). Change in percentage of straight, and 1st order and 2nd order bent trees between February and August was about the same as for rectangular configurations.

Site 2 Species

In August 2000, prior to the ice storm, loblolly and shortleaf pine differed ($P \leq 0.05$) in height (7.9 and 6.3 m, respectively) and diameter (14.0 and 11.2 cm, respectively). The species also differed for each damage rating ($P < 0.05$) (Table 3). Damage score was positively correlated with height ($R^2 = 0.41$, $P < 0.05$) and diameter ($R^2 = 0.45$, $P < 0.05$), indicating that larger trees within each species were more susceptible to acute damage than smaller trees.

Site 3 Thinning

The nonthinned stand had more unbroken trees, fewer severely bent (2nd order), and fewer with severe lean (Table 4) as compared to the thinned stand. It is likely that most severely bent trees will not recover at this site. Acute damage (sum of bottom $\geq$ 50% stem broken, severely bent, and severe lean classes) was estimated at 4.7 and 22.8% for the nonthinned and thinned stand, respectively.

TABLE 2. Percentage of 7-Year-Old Loblolly Pine Trees in Various Ice Storm Damage Classes in Site 1 Multi-Row Configurations, West-Central Arkansas

Multi-row configuration	Stand density (TPH)	Damage class									
		Straight		Top broken[1]	Stem broken[1]	1st order bend		2nd order bend		Lean[1]	Sigmoid-shaped[2]
		Feb.	Aug.			Feb.	Aug.	Feb.	Aug.		
		(%)									
5 × (1.2 m × 2.4 m)	1,980	4.0[3]	45.8	1.7	3.4	23.7	9.3	58.7	3.0	6.2	30.3
4 × (1.2 m × 2.4 m)	1,580	12.0	58.3	1.4	3.5	34.1	11.8	49.2	3.5	2.5	21.4
3 × (1.2 m × 2.4 m)	1,580	16.1	71.1	5.2	1.5	37.3	8.3	41.9	2.8	2.0	15.5
2 × (1.2 m × 2.4 m)	1,580	13.0	63.2	1.7	5.9	29.0	7.7	48.3	0.6	3.8	22.9
LSD (0.05)[4]		11.7	10.2	3.6	NS	9.2	NS	3.7	NS	NS	12.6

[1] Broken and leaning trees were disregarded from the August evaluation.
[2] The sigmoid class was rated in August only.
[3] Analysis was based on square root-transformed data but untransformed means are shown.
[4] Least significant difference for comparing means within columns.

TABLE 3. Percentage of 9-Year-Old Loblolly and Shortleaf Pine Trees in Various Ice Damage Classes at Site 2, West-Central Arkansas

	Damage class[1]				
Pine species	Unbroken	Top broken	Stem broken	Severe lean	Damage score[2]
			(%)		
Loblolly	68.5***[3]	21.5***	10.0***	0.8*	32.3***
Shortleaf	75.7	18.0	6.3	1.4	25.7

*, *** Species means differ by *F*-test at P ≤ 0.05 and 0.001, respectively.
[1] Damage classes include top ≤ 25% broken, stem broken with ≤ 5 live branches remaining, and stem leaning ≥15°.
[2] Overall damage score was the ratio of trees with broken tops, broken stems, and severe lean to total trees.
[3] Analysis was based on square root-transformed data but untransformed means are shown.

TABLE 4. Percentage of 17-Year-Old Loblolly Pine Trees in Various Ice Damage Classes in Site 3 as Affected by Stand Density, West-Central Arkansas

	Damage class					
Stand density	Unbroken	Top ≤10% broken	Middle 11 to 50% broken	Bottom ≥ 50% broken	Severely bent	Severe lean
			(%)			
High[1]	31.0*[2]	55.1	8.5	2.5	2.0*	0.2*
Low	17.4	42.9	11.2	4.9	10.3	7.6

*, ** Stand density means differ by *F*-test at P ≤ 0.05 and 0.01, respectively.
[1] High and low densities had about 1,600 and 150 trees/ha, respectively.
[2] Analysis was based on square root-transformed data but untransformed means are shown.

DISCUSSION

Agroforestry stands may be distinguished from forestry plantations in both design (usually lower stand density and wider alleys) and management (commodities such as hay and livestock are produced on the same land unit as wood fiber). These silvicultural practices could differentially affect crown symmetry of individual trees and, by extension, alter the stand's susceptibility to ice damage (Fountain and Burnett, 1979; Schultz, 1997; Zeide and Sharer, 2000). There are no known reports of post-storm damage assessments in pine agroforestry stands.

Amateis and Burkhart (1996) examined ice damage in a loblolly pine spacing study following a storm with heavy ice loading and high winds. Within-row and row spacing ranged from 1.2 to 3.6 m. Damage was so severe that it was generally not influenced by tree spacing. They noted, however, that damage might be associated with spacing, stand density, or stocking under less severe storm conditions. In this study, ice damage to 7-year-old trees in rectangular configurations was generally a function of spacing, stand density, and diameter. Top and stem breakage increased with increased spacing and diameter, and trees tended to bend, rather than break, at narrow spacings. Data were conflicting for undamaged trees, as the percentage increased with row spacing but decreased as within-row spacing increased.

The two stand densities (1,580 and 1,980 TPH) in the four multi-row configurations did not consistently differ in ice damage. Intuitively, it would seem that tree crowns in exterior rows of multi-row configurations might be more asymmetric and suffer more ice damage than crowns in interior rows. We did not measure this effect, but no obvious differences were observed.

Stem bending is perhaps the first visual damage assessment made by the landowner, but there have been few reports of recovery of bent trees. In the absence of empirical data, it was unclear whether, or at what rate, the bent trees would recover. The general rules-of-thumb were that young loblolly trees < 4.5 m tall generally recover after a storm (Barry et al., 1998), trees bent < 40% from the vertical may completely recover, and those with greater bending may have permanent damage (Schultz, 1997). We found that stems were more flexible than previously thought because trees averaging 6.2 m tall with as much as 54° bend recovered from ice loading. Recovery was rapid; 53.3% of trees in rectangular configurations were straight 8 months after the storm. Most trees with a 1st order bend recovered rapidly. Trees with a 2nd order bend also recovered, albeit more slowly. Many of these assumed a sigmoid shape from which we anticipate further recovery with time.

The 9-year-old loblolly-shortleaf stand had about 10% acute damage. Height and diameter were positively associated with ice damage in this stand, unlike the younger stand. For this stand, but not the 7-year-old stand, we support previous findings (Amateis and Burkhart, 1996; Cain and Shelton, 2002) that diameter and height were associated with stem and top damage of loblolly pine.

Loblolly pine had more damage than shortleaf pine at site 2, perhaps because its longer needles accumulated more ice. Shortleaf pine is native to this region while loblolly pine is not (Schultz, 1997), so increased ice damage could reflect a lack of adaptation. Slash pine (*P. elliottii* Engelm.) in northern Louisiana, however, does not necessarily have more ice damage than loblolly pine (Shepard, 1981). Loblolly pine had about 25% greater height and diameter growth than shortleaf pine, so managers must balance its superior growth rate against its increased susceptibility to ice damage. We consider that the increased ice damage susceptibility of loblolly pine, relative to shortleaf pine, is sufficiently small to justify its continued production in the region.

Thinning a 17-year-old stand increased its susceptibility to stem bending and leaning 2 years later compared to the non-thinned treatment, demonstrating that management was important in influencing damage. Belanger et al. (1996) observed that there were nearly 2.5 times as many trees with broken stems and stem bending in recently thinned vs. nonthinned stands of 19-year-old loblolly pine, although they did not make a statistical comparison. Thinning from below has been recommended for minimizing ice storm damage to loblolly pine (Shepard, 1978; Fountain and Burnett, 1979), and that strategy might have lessened damage to the 17-year-old stand. Further, volume growth of the low density stand might be slower to recover than in the high density stand (Belanger et al., 1996). The maintenance of high tree density minimized breakage, severe bending, and leaning.

In conclusion, damage was assessed in pine agroforestry stands following a severe ice storm in December 2000. Ice damage differed as a function of stand age, design, and management. Wider tree spacing or lower stand density of 7-year-old trees increased stem diameter and breakage, while closer spacing increased bending. However, 7-year-old loblolly pine stems were remarkably flexible under ice loading, and there was a five-fold increase in the percentage of straight trees 8 months after the storm. Nine-year old loblolly pine had more ice damage than shortleaf pine ($P < 0.001$), but the difference may be small relative to loblolly pine's growth advantage. Thinning a 17-year-old stand from above increased ice damage compared to an nonthinned stand.

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